(NASA-TM-86139) AXIONS, NEUTRINOS AND STRINGS: THE FORMATION OF STRUCTURE IN AN SO(10) UNIVERSE (NASA) 10 p HC A02/MF A01 CSCL 03B
N84-33317
Unclas
G3/90 20360

NASA

Technical Memorandum 86139

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F. W. Stecker

JULY 1984

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

NASA TM 86139

July, 1984

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F.W. Stecker
Laboratory for High Energy Astrophysics
NASA Goddard Space Flight Center
Greenbelt, MD 20771

To be published in the Proceedings of the Fermilab "Inner Space/ Outer Space" Workshop

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F.W. Stecker
Laboratory for High Energy Astrophysics
NASA Goddard Space Flight Center
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I will report on work with Qaisar Shafi where we consider a class of grand unified theories in which cosmologically significant axion and neutrino energy densities arise naturally. To obtain large scale structure we consider (1) an inflationary scenario, (2) inflation followed by string production, and (3) a non-inflationary scenario with density fluctuations caused solely by strings. We show that inflation may be compatible with the recent observational indications that $\Omega < 1$ on the scale of superclusters, especially if strings are present.

Axions with a cosmologically significant energy density provide an important component in the mechanism for generating structure in the universe on scales up to 10^{15} $M_{\odot}$ [1,2]. An SO(10) GUT framework which leads to the production of cosmologically significant axions has been given[3].

As an example of a grand unified theory which gives $\Omega_a \simeq \Omega_{\nu}$, consider an SO(10) model[3] where both the Pecci-Quinn[4] U(1) symmetry and the local B-L symmetry are broken at a scale of order 10^{12} GeV. The value of the intermediate scale is not put in by hand, but is determined from the renormalization group equations of the gauge couplings. From the results of Reference (5), it follows that $\Omega_a \simeq 0.1$-1.

The breaking of B-L at scale f_a, caused by a $\underset{\sim}{126}$ -plet of Higgs fields, induces a Majorana mass term for the right-handed neutrino ν_{Ri} of order $h_i f_a$, where h_i denotes the Yukawa coupling of the i^{th} generation. The breaking of SU(2) x U(1) to $U(1)_{em}$ is achieved by a Higgs $\underset{\sim}{10}$ plet and gives rise to Dirac mass terms $m_{\nu i}^{(D)}$ linking the left

and right-handed neutrinos. Moreover, it can be shown that an effective Majorana mass term for the left-handed neutrino ν_{Li}, of order $c_i \approx h_i\ (\lambda_1/\lambda_2)\ \langle\phi_{10}\rangle^2/f_a$ is also induced[6]. Here λ_1 denotes the quartic higgs coupling between the $\underset{\sim}{126}$ and the $\underset{\sim}{10}$, λ_2 is the quartic self-coupling of $\underset{\sim}{126}$, and $\langle\phi_{10}\rangle$ is the vacuum expectation value of the $\underset{\sim}{10}$. With $f_a \approx 10^{12}$ GeV, λ_1/λ_2 of order unity, and $h_i \sim O(g^2)$ (where g denotes the SO(10) gauge coupling), c_i is in the electron volt range. Diagonalization of the neutrino mass matrix (neglecting, for simplicity, mixings between generations) yields the eigenvalues $(m_{\nu_i})_{heavy} \approx h_i f_a$, $(m_{\nu_i})_{light} \approx c_i - (m_{\nu i}^{(D)})^2/\ (m_{\nu i})_{heavy}$.

Due to the presence of the c_i term, the light neutrino of each generation can have a mass in the electron volt range. The second term involving the Dirac masses can be made small so that the masses of the different neutrino flavors can be almost degenerate, providing a possible explanation for the lack of observed neutrino oscillations.[6] It is this possibility which will be of particular interest to us here.

We now discuss the implications of significant axion and neutrino energy densities for the evolution of structure in the universe. Two mechanisms for producing density fluctuations in the early universe have been extensively discussed, viz., inflation[7] and strings[8]. Recently, it was pointed out[9] that one could obtain another sceniaro in which inflation is followed by string production. The inflationary phase is associated with the transition from SO(10) to $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. It can be implemented by generalizing the arguments of ref. (10) where the SU(5) model is discussed. The breaking o B-L and the U(1) symmetry can occur during, or at the end of the inflationary era. The spectrum of density fluctuations produced in this scenario is scale invariant.

According to recent observations[11], the value for Ω obtained on scales up to $\sim 10^{15}\ M_\odot$ is $\approx 0.2 \pm 0.1$, considerably less than unity, the value predicted by an

inflationary cosmology. As a reasonable upper limit for Ω_{sc} of superclusters[12], we may take $\Omega_{sc} \lesssim 0.5$. Therefore, since axions and baryons cluster on scales smaller than rich clusters and superclusters[1], their contribution to Ω must be $\lesssim 0.5$. The balance of the total Ω in the universe must therefore be in the mass density of the neutrino component if we are to have Ω=1 as predicted by inflationary cosmology.

We must therefore require that the neutrinos be light enough so that they will not cluster on scales below ~ 10^{16} $M_{\odot}$. In order to arrange this, especially since the neutrino Jeans mass drops significantly between the redshift z_{nr} when the neutrinos become nonrelativistic and the present time, we invoke neutrino phase space limits using the arguments of Tremaine and Gunn[13] in reverse to get an upper limit on m_{ν}. These authors find that for neutrinos to be able to cluster on the scale of rich clusters, their mass must be greater than ~ 4 $h_{50}^{-1/2}$ eV (where h_{50} is the Hubble constant in units of 50 $kms^{-1}Mpc^{-1}$). We require a mass less than this limit to prevent clustering of the neutrino component.

The neutrino contribution to Ω is $\Omega_{\nu} = 4.56 \times 10^{-2}\, m_{\nu}(eV) N_f\, h_{50}^{-2}\, T_{2.8}^{3}$, where N_f is the number of neutrino flavors of approximately equal mass and $T_{2.8}$ is the present temperature of the cosmic blackbody radiation in units of 2.8 K. We require Ω_{ν} to be $\gtrsim 0.5$ so that the total $\Omega = 1$. Thus, one needs at least three flavors of neutrinos, each of approximately 3-4 eV. As discussed above, this situation is readily obtained in the SO(10) model (see above). (If the efficiency of neutrino clustering is low, m_{ν} could be somewhat larger.)

The maximum neutrino Jeans mass for three neutrinos of roughly equal mass is[14] $M_{J\nu}^{*} = 2.7 \times 10^{18}\, [m_{\nu}(eV)]^{-2} M_{\odot}$, which, for $N_f = 3$ and $m_{\nu} \simeq 3.6$ eV gives $M_{J\nu}^{*} \simeq 2 \times 10^{16}\, M_{\odot}$. The corresponding spatial scale at present for pancaking structure would be ~ 150 Mpc. This scale may correspond to the "superpancaking" scale[15] for clustering of superclusters.[16] Structure on this scale would correspond to density perturbations $\delta \equiv \delta\rho/\rho$ just becoming nonlinear (δ = 0.5-1) at the present time (z = 0).

The spectrum of linear perturbations in a universe dominated by axions and neutrinos is readily estimated by adopting the arguments previously given for a baryon-neutrino universe[17]. It is convenient to define $\xi = \Omega_a / (\Omega_a + \Omega_\nu)$ such that $\xi \leq 1/2$ (We assume, for simplicity, that $\Omega_b << \Omega_a, \Omega_\nu$).

For $z < z_{eq} \approx 0.93\times10^4 (1-\xi)^{-1} \Omega_\nu h_{50}^2 T_{2.8}^{-4}$ the neutrino Jeans mass decreases as $(1+z)^{3/2}$. Neutrino perturbations on scales below $M^*_{J\nu}$ are erased at $z \approx z_{eq}$. The axion perturbations, however, grow like $\delta_\alpha \propto t^\alpha \propto (1+z)^{-3\alpha/2}$ where $\alpha = (\sqrt{1+24\xi} - 1)/6$. Thus,

$$\delta_a (z) \approx \delta_a (z_{eq}) \left(\frac{1+z_{eq}}{1+z}\right)^{3\alpha/2} \tag{1}$$

This continues until $z \approx z_M$ when the neutrino Jeans mass becomes $\approx M$,

$$(1+z_M) \approx \left(\frac{M}{M^*_{J\nu}}\right)^{2/3} (1+z_{eq}) \tag{2}$$

For $z < z_M$ the overall density fluctuation $\delta\rho/\rho \propto t^{2/3} \propto (1+z)^{-1}$. Thus,

$$\frac{\delta\rho}{\rho} (z<z_M) \approx \xi\, \delta_a(z_M) \left(\frac{1+z_M}{1+z}\right) \approx \xi\, \delta_a(z_{eq}) \left(\frac{1+z_{eq}}{1+z}\right) \left(\frac{M}{M^*_{J\nu}}\right)^{(2/3-\alpha)} \tag{3}$$

As a rough approximation, $\delta_a(z_{eq}) \approx$ constant when $M < M^*_{J\nu}$ for a scale invariant initial spectrum. This gives

$$\frac{\delta\rho}{\rho} \propto M^{(2/3-\alpha)} \qquad (M < M^*_{J\nu}) \tag{4}$$

which is an <u>increasing</u> function of M since $\alpha < 2/3$. For $M > M^*_{J\nu}$, the neutrino perturbations are not damped and $\delta\rho/\rho \propto M^{-2/3}$.

From this discussion we conclude that even in the most optimistic case

where $\xi = 1/2$, $\alpha = 0.43$, so that the scales between the present neutrino Jeans mass and $M^*_{J\nu}$ may not collapse before $M^*_{J\nu}$. We thus run into the timing problems which are becoming well known for the neutrino pancaking scenario. In particular, it is hard to envision the development of quasars[18] and substructure[19] with such a model.

The presence of strings, which provide an additional source of density fluctuations, can eliminate the above difficulty. Assume that topologically stable strings, with mass per unit length characterized by a superheavy (GUT) scale, appear at or near the end of the inflationary phase[10]. (This is readily achieved in the present case either by appending a new spontaneously broken global U(1) symmetry to the SO(10) model or using an E_6 model. It can also be obtained naturally in a Kaluza-Klein model (Wetterich, private communication)). The strings can intercommute forming closed loops[20] which produce axion density perturbations $\delta_a(z_{eq}) \propto M^{-1/3}$ below the Jeans mass scale. It then follows that

$$\frac{\delta\rho}{\rho} \propto M^{(1/3-\alpha)} \qquad (M < M^*_{J\nu}) \qquad (5)$$

as compared with eq (4).

For $\xi = 1/2$, $\alpha = 0.43$ and $\delta\rho/\rho \propto M^{-0.1}$. Therefore, if $\delta\rho/\rho \sim O(1)$ on scales ~ 10^{16} - 10^{17} M_0 at z=0 as suggested by Dekel[15], scales ~ 10^{10} M_0 go non-linear at z ≈ 4, corresponding to the epoch of quasar formation. Thus, in the presence of axions and neutrinos, an inflationary scenario supplemented by strings appears to offer a better prospect of explaining the observed large scale structure in the universe than one without strings. (The later case, however, may be helped by the effects of axion perturbation growth in the radiation dominated area).

Suppose we dispense with inflation and assume that the density fluctuations are produced solely by strings. In this case, since Ω need not be unity, ξ can be greater than 1/2 and α can be > 0.434. (Of course, we need have only one ν flavor in the eV

mass range to get Dekel's[15] scale.) In particular for $\Omega_a >> \Omega_\nu$, $\alpha = 2/3$. A natural extension of SO(10) which gives the desired strings is provided by E_6 symmetry breaking to SO(10) at a scale $\eta \simeq 10^{16}$ GeV. The energy per unit length of the strings formed is $\mu \simeq \eta^2 \simeq 10^{32}$ GeV^2. Then at z=0

$$\frac{\delta\rho}{\rho}\,(M^*_{J\nu}) \simeq 30\ G\mu\ (1+z_{eq}) \simeq O(1). \qquad (6)$$

Thus, neutrino perturbations would be on the verge of becoming non-linear at the "superpancake" scale, as suggested by the observations[15,16].

We are grateful to Dr. Alexander Vilenkin for many helpful discussions.

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